METHOD AND APPARATUS FOR FILTERING
INTERFERENCE AND NONLINEAR DISTORTIONS

BACKGROUND OF THE INVENTION

5 . The present invention relates to electronic communications systems, and more particularly to a method and apparatus for filtering interference and nonlinear distortions in a signal communicated from a transmitter to a receiver via a communication path.

The invention is particularly suited for use in
10 connection with a television distribution system, such as a hybrid fiber/coax (HFC) network, in which a subscriber terminal such as a set-top box or cable modem receives television and/or data signals from the distribution system "headend" via a " downstream" communication path
15 and sends information back to the headend on an " upstream" return path. In such an environment, the interference filtered by the present invention is often referred to as " ingress" or " ingress noise" and the nonlinear distortions of concern comprise composite

second order (CSO) and composite triple beat (CTB) distortions.

Hybrid fiber/coax networks, which are based on branch and tree architecture, provide a cost-effective means for delivering downstream broadband services such as analog/digital video and high-speed data. In addition, they provide subscribers with high-speed data upstream transmission, for example, in the 5-42 MHz portion of the RF spectrum. Cumulative ingress noise is the main impairment in the return-path portion of HFC networks. The types of ingress noise, which appear on the return-path, can be classified as follows:

A. Narrowband short-wave signals, originating from radio stations and other sources, coupled to the return-path cable plant at the subscriber location or in the distribution plant.

B. Common mode distortion originating from non-linearities in the cable plant.

C. Location specific interference generated by an electrical device at the subscriber location.

See, e.g., C. A. Eldering, N. Himayat, and F. M. Gardner,
"CATV Return Path Characterization for Reliable
Communications", *IEEE Communications* 8, 62-68 (1995).
The amount of cumulative ingress noise in the return-path

5   network is essentially the limiting factor in determining
the maximum number of simultaneous users and the maximum
data transmission rate that can be achieved.

Video signals sent to set-top boxes are also often
subject to " burst/impulse noise" originating from peak

10   Composite Second Order (CSO) and/or Composite Triple Beat
(CTB) distortions. These distortions are generally
present at known frequencies, which depend upon the
television frequency plan used for the analog video
signals. In cable television systems, such frequency

15   plans include the integrally-related-carrier (IRC) plan
and the harmonically-related-carrier (HRC) plan. CSO and
CTB distortions can lead to video blocking and visually
degraded areas in a television picture. One method for
addressing the CSO/CTB distortion problem in multi-

20   channel AM-VSB (amplitude modulated vestigial

sideband)/QAM (quadrature amplitude modulation) video

transmission systems and the like is disclosed in co-

pending, commonly assigned U.S. patent application no.

09/170,852 filed October 13, 1998 and entitled "Method

5   and System for Enhancing Digital Video Transmission To A

Set-Top Box."   In the system disclosed in that patent

application, the performance of hybrid analog and digital

video transmission systems is improved by determining the

relative magnitude and frequency locations of nonlinear

10   distortions, identifying the analog channel frequency

plan, and then selecting a digital channel map based

thereon.

It would be advantageous to have a robust and cost-

effective method and apparatus for filtering interference

15   (such as ingress noise or other interference types) and

nonlinear distortions in a signal communicated from a

transmitter to a receiver via a communication path, such

as a return path signal from a set-top box or the like.

It would be further advantageous to provide such a method

20   and apparatus that operate adaptively, so that

interference (e.g., ingress) is efficiently filtered even
when the frequency of the interference peaks changes over
time. Such a method and apparatus should enable a
plurality of interference peaks to be filtered, and

5 should automatically adapt to changing conditions in the
interference.

It would be still further advantageous to provide a
method and apparatus for filtering nonlinear distortion
in a signal communicated from a transmitter to a receiver

10 via a communication path. Such a method and apparatus
would be particularly useful in the downstream channel of
an HFC cable television distribution system, where either
an IRC or HRC frequency plan is used.

The present invention provides methods and apparatus

15 enjoying the aforementioned and other advantages.

SUMMARY OF THE INVENTION

In accordance with the present invention, a method and apparatus are provided for filtering interference in a signal communicated from a transmitter to a receiver via a communication path. The transmitter is momentarily disrupted from transmitting over the communication path, e.g., by placing it in an idle state. During the momentary disruption, the receiver analyzes interference on the communication path to determine the frequency of at least one noise peak of the interference. Information is communicated from the receiver to the transmitter identifying the frequency of the at least one interference noise peak. Based on this information, the transmitter pre-distorts the signal to accentuate the signal magnitude at the identified frequency or frequencies of the interference peak(s). The pre-distorted signal is then transmitted by the transmitter to the receiver, which filters the pre-distorted signal to attenuate the signal magnitude at the identified frequency or frequencies.

In an illustrated embodiment, the receiver performs a real or complex signal frequency analysis on the interference to determine the frequency peak(s) thereof. The filtering at the receiver can use, for example, a transfer function that is the inverse of the transfer function used to pre-distort the signal at the transmitter. In one possible implementation, the filtering at the receiver uses the Z-transform transfer function:

$$H(z) = \frac{1 + 2\,\mathrm{Re}(\alpha)z^{-1} + z^{-2}}{1 - 2\,\mathrm{Re}(\alpha)R \cdot z^{-1} + R^2 \cdot z^{-2}}$$

where $\alpha = \exp(2j\pi\phi)$, ϕ is the normalized center frequency of the filter, and R is a constant. The pre-distortion at the transmitter can implement the inverse transfer function $H(z)^{-1}$.

A power threshold detection can be used during the analysis to identify the frequency location(s) of the interference peak(s). For example, only peaks exceeding a predefined power threshold level might be identified

for pre-distortion at the transmitter and subsequent filtering at the receiver.

In an adaptive method, the transmitter is periodically disrupted from transmitting over the communication path. Interference on the communication path is analyzed at the receiver during the periodic disruptions, and information is communicated·from the receiver to the transmitter identifying changes in the interference peak(s) determined during the periodic disruptions. The transmitter then pre-distorts the signal to accentuate the signal magnitude in accordance with the changes of the interference peaks.

Also disclosed are a method and apparatus for filtering nonlinear distortion in a signal communicated from a transmitter to a receiver via a communication path. The signal is pre-distorted at the transmitter to accentuate the signal magnitude at a fixed frequency where the nonlinear distortion takes place. The pre-distorted signal is transmitted to the receiver, which provides

filtering to attenuate the signal magnitude at said fixed
frequency.

If the signal is, for example, an integrally-related
carrier (IRC) television channel signal having composite
second order (CSO) and composite triple beat (CTB)
distortions present at different fixed frequencies, the
CSO and CTB distortions are filtered by pre-distorting
the signal at the transmitter to accentuate the signal
magnitude at a first fixed frequency where the CSO
distortion resides, and at a second fixed frequency where
the CTB distortion resides. The pre-distorted signal is
then filtered at the receiver at the first and second
fixed frequencies.

If the signal is, for example, a harmonically related
carrier (HRC) television channel signal having composite
second order (CSO) and composite triple beat (CTB)
distortions present at a common fixed frequency, the CSO
and CTB distortions are filtered by pre-distorting the
signal at the transmitter to accentuate the signal
magnitude at the common fixed frequency. The pre-

distorted signal is then filtered at the receiver at the

common fixed frequency.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a block diagram of illustrating a cable television headend or cable modem termination system (CMTS) with a return path receiver;

5   Figure 2 is a more detailed block diagram of the return path receiver component of Figure 1;

Figure 3 is a detailed block diagram of one embodiment of a burst receiver that can be used in the receiver of Figure 2 in accordance with the invention;

10   Figure 4 is a detailed block diagram of an alternate embodiment of a burst receiver that can be used in the receiver of Figure 2 in accordance with the invention;

Figure 5 is a block diagram of an example second-order notch filter structure that can be used in a receiver in

15   accordance with the invention;

Figure 6 is a graph illustrating a simulated baseband 256-QAM spectrum with a narrowband interference peak located at 0.5-MHz off the center of the channel with $C/(N+I)=0dB$;

Figure 7 is a graph illustrating a simulated baseband 256-QAM spectrum of a pre-distorted signal to be transmitted in accordance with the invention;

Figure 8 is a graph illustrating the simulated 256-QAM

5   baseband spectrum of the signal of Figure 7 after the interference has been removed by filtering at the receiver in accordance with the invention;

Figure 9 is a graph illustrating the amplitude response of a notch filter that can be used at the receiver for

10   filtering the pre-distorted signal;

Figure 10 is a graph illustrating the phase response of a notch filter that can be used at the receiver for filtering the pre-distorted signal;

Figure 11 is an illustration of a simulated quadrant of

15   a 256-QAM I/Q constellation with narrowband interference that has not been filtered in accordance with the invention; and

Figure 12 is an illustration of a simulated quadrant of
a 256-QAM I/Q constellation with narrowband interference
that has been filtered in accordance with the invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention provides techniques for filtering both interference and nonlinear distortions in a communication system. For example, the invention is

5   useful to filter ingress noise which may include, for example, narrowband interference, common mode distortion and location specific interference in an upstream channel (e.g., return path) of a cable television system. The invention may also be used to filter nonlinear

10   distortions such as CSO and CTB distortions, which may, for example, be present in the downstream path of a cable television system. Additional uses of the invention for other interference and distortion types will be apparent to those skilled in the art.

15   Figure 1 illustrates, in simplified block diagram form, a cable modem termination system (CMTS) at a cable television headend. The CMTS is controlled by a computer processor (CPU) 10 which communicates with the other CMTS components over a bi-directional bus coupled to a media

20   access controller (MAC) 12. The MAC 12 controls the

physical layer of the communication signals and

coordinates various aspects of the data carried by the

signals such as the time data is sent, the time data is

received, etc. The MAC 12 also receives signals from a

5 return path receiver 20 which, in turn, receives signals

from a remote subscriber terminal (e.g., a cable modem or

set-top box). The data signals to be transmitted are

provided by the MAC to a QAM modulator 14 for modulation

in a conventional manner. An upconverter 16 converts the

10 output of the QAM modulator to a suitable radio frequency

(RF) for transmission over, e.g., a bi-directional HFC

network 22. The CMTS is coupled to the HFC network via a

diplexer 18 in a conventional manner.

The front-end of the return-path receiver 20 converts a

15 bursty analog signal received from the subscriber

terminal to a sampled digital signal, which can be fed to

an off-line (i.e., non-real time) Digital Signal

Processing (DSP) chip 38 in the receiver, as illustrated

in Figure 2. In order to filter interference (e.g.,

20 narrowband interference such as ingress), the

interference must first be detected. To do this, an

initialization process is commenced wherein the digital

transmitter (e.g., QPSK or QAM) in the cable modem (CM)

or at the set-top box is placed in an idle mode, so that

5   only the cumulative interference will be received by the

return path receiver 20 at the CMTS. The off-line DSP 38

provided within the return path receiver 20 analyzes the

received noise. This analysis can be performed using a

complex signal frequency analyzer which uses, for

10   example, a Discrete Fourier Transform (DFT) algorithm.

The spectral power density of the interference is

significantly higher than that of the white Gaussian

noise (WGN), and the noise peaks can easily be identified

using a threshold power detector. The threshold level

15   can be set, for example, to be 10-dB higher than the WGN

floor to assure that only large interference peaks are

being identified. To achieve, for example, 10-kHz

interference peak resolution in a 3.2-MHz data channel

(worst-case), 640 sampling points are required for the

20   DFT.

Once the frequencies of the interference peaks have been determined, information identifying these specific frequencies is transmitted to the subscriber terminal via the downstream QAM modulator 14, upconverter 16 and

5   diplexer 18 as shown in Fig. 1. It is noted that although a QAM modulator is shown for purposes of illustration, any suitable form of digital modulation can be used to transmit the interference peak identification information to the subscriber terminal. As an

10   alternative, an alternate channel (which can be analog or digital) could be used to pass this information to the subscriber terminal.

Relevant portions of one possible implementation of the return path receiver 20 are illustrated in block diagram

15   form in Figure 2. It is noted that the illustrated portions are provided as an example only, and that other implementations will be apparent to those skilled in the art. In a cable television implementation, the receiver portions illustrated can be provided in a CMTS or other

20   headend embodiment.

The HFC network 22 is coupled to a tuner 30 provided in

the receiver. A desired upstream signal received from

the HFC network, such as a data signal, is tuned using

tuner 30 and passed to an analog to digital converter

5   (A/D) 32. The digitized signal from A/D 32 is passed to

an appropriate receiver, such as burst receiver 36 and a

DSP 38. The DSP performs a real or complex signal

frequency analysis of the return path signals to

determine the frequency of each of the interference

10   peaks. The DSP sends information indicative of the

frequency of each peak (e.g., the filters' coefficient

data) to the microprocessor 40 to set up notch filters in

the burst receiver 36. This information is also

communicated to the subscriber's set-top box or cable

15   modem for use in setting up complementary pre-distortion

filters. The purpose of the pre-distortion filters in

the subscriber's cable modem or set-top box is to

accentuate the transmitted return path (upstream) signal

at the frequencies where the interference is expected to

20   occur at the receiver. Corresponding notch filters at

the CMTS will then attenuate the same frequencies at the

return path receiver, thereby effectively filtering out

the effect of the interference. The attenuation at the

burst receiver 36 not only filters out the interference;

it also returns the signal level to its proper magnitude

5   at the interference peak frequencies.

Figures 3 and 4 illustrate further detail for two

different embodiments of a return path receiver using

notch filters in accordance with the present invention.

The receivers illustrated in these figures can be used to

10   provide the functions of return path receiver 20 shown in

Figure 1. In particular, the intermediate frequency (IF)

return path signal from the tuner 30 of Figure 2 is input

to an A/D converter 32 (Figure 2), which digitizes the

signal and passes it to I and Q phase quadrature mixers

15   52, 54 respectively (Figure 3 or 4). In the embodiment

of Figure 3, square-root Nyquist filters 56, 58 filter

the I and Q signals, and pass them to respective notch

filters (NF) combined with ÷4 decimation filters 60, 62,

thereby providing down-sampled I and Q signals that have

20   been attenuated back to normal levels at the interference

frequency peaks. In the embodiment of Figure 4, notch
filters 51 are provided immediately prior to quadrature
mixers 52, 54 instead of being combined with the
decimator filters 61, 63.

5   The filtered and down-sampled I and Q signals are
passed to a feed forward equalizer (FFE) 64 and decision
feedback equalizer (DFE) 66 for conventional
equalization. A forward error correction (FEC) decoder
68 then processes the equalized I and Q signals in a
10   conventional manner. Acquisition and tracking loop 70
enables the receiver to properly acquire and track the
received signal, as well known in the art.

The following difference equation describes a second-
order digital notch filter design that can be used to
15   implement the invention:

$$y(n) = b_0 \cdot x(n) + b_1 \cdot x(n-1) + b_2 \cdot x(n-2) - a_1 \cdot y(n-1) - a_2 \cdot y(n-2)$$

where:

x(n) and y(n) are the time-discrete input and
output sequences,

$b_2 = b_0 = 1, \ b_1 = 2\text{Re}(\alpha),$

$a_1 = -2R^2 \cdot \text{Re}(\alpha), \ a_2 = R^2,$ and

$\alpha = \exp(2j\pi\phi)$

ϕ = the normalized center frequency the notch, and

5   R is a constant related to the notch magnitude.

Thus, only two coefficients are needed for this filter.

The second-order notch filter structure, which is shown

in Fig. 5, is known as a direct form II structure. The

transfer function or the Z-transform of the notch filter

10   80 is described by the following equation:

$$H(z) = \frac{1 + 2\,\text{Re}(\alpha)z^{-1} + \cdot z^{-2}}{1 - 2\,\text{Re}(\alpha)R \cdot z^{-1} + R^2 \cdot z^{-2}}$$

15   The pre-distortion filter at the subscriber terminal

transmitter has exactly the inverse transfer function as

the second-order notch filter shown above [H(z)$^{-1}$]. The

pre-distortion filters can, for example, be inserted

after the symbol mapper for a QPSK (quadrature phase

20   shift keyed) or QAM (quadrature amplitude modulation)

implementation, and before a programmable transmitter
pre-equalizer that is used to cancel the effects of
intersymbol interference (ISI). It is noted that
although a notch filter is described herein for use with
5   the return path receiver, other types of filtering may be,
used instead to provide the same or similar results.

Figure 6 illustrates a simulated baseband 256-QAM
spectrum 82 with a narrowband interference peak 83
located 0.5-MHz off the center of the channel and with
10   C/(N+I)=0dB.

Figure 7 illustrates the spectrum 84 of the simulated
baseband 256-QAM spectrum with the pre-distortion 85
added at the transmitter.

Figure 8 shows the simulated baseband 256-QAM spectrum
15   86 at the upstream receiver after the narrow interference
peak 83 and pre-distortion 85 have been removed.

Figures 9 and 10 illustrate the amplitude and phase
responses 88, 90 respectively, of the second order notch
filter of Figure 5, as a function of the normalized
20   frequency.

Figure 11 shows a simulated single quadrant 92 of the

256-QAM constellation when the interference peak

illustrated in Figure 6 is present. It is clear from

this figure that the received signal contains many

5   errors.

Figure 12 shows a simulated single quadrant 94 of the

256-QAM constellation in the presence of the interference

peak, but after the application of the interference

filtering technique of the present invention. The

10   simulation results indicate an error-free reception for

the demodulated 256-QAM signal.

In order to further refine the present invention, the

filtering of interference such as ingress noise can be

made adaptive. In particular, between upstream burst

15   intervals, (e.g., once every second) the subscriber

terminal transmitter may be idled to " quiet" the return

path. This will enable the CMTS to monitor the ingress

peaks on the quieted return path. The off-line DSP chip

38 at the return-path receiver in the CMTS can determine

20   if the previously detected ingress peaks are still

present or if there are new ingress peaks. The updated

information (parameter α in the transfer function for

$H(z)$) on the frequency of the current interference

peak(s) is then sent to the subscriber terminal (e.g.,

5   set-top or cable modem) transmitter via the downstream

modulator to enable and/or disable appropriate pre-

distortion filters at the return-path transmitter. At

the same time, appropriate notch filters at the return

path receiver are enabled and inappropriate notch filters

10   are disabled.

A variation of the techniques described above can be

applied to downstream signal (e.g., digital video)

transmission to subscriber terminals to overcome the

effect of nonlinear (CSO/CTB) distortions. The location

15   of CSO and CTB distortions in an HFC network depends on

the cable TV frequency plan used for the analog video

signals. The two most widely used cable TV frequency

plans are the integrally-related-carrier (IRC) and

harmonically-related-carrier (HRC) plans. In the IRC

20   plan the first picture carrier frequency is located at

55.2625-MHz with successive picture carriers located six

MHz apart up to 1-GHz. In the HRC frequency plan, the

picture carrier frequencies are downshifted 1.25-MHz

compared with the corresponding picture carriers in IRC

5   plan. The advantage of the HRC plan is that the CSO and

CTB distortion products fall on the picture carrier, and

thus their effect becomes almost invisible. In the IRC

plan, the CSO distortions are located ± 1.25-MHz from the

corresponding picture carrier frequency, and thus can

10   become visible.

The following Table 1 shows the various options for the

IRC and HRC frequency plans:

**Table 1 - The location of CSO and CTB distortions
relative to the QAM channel center frequency.**

Frequency Plan	CSO Distortions	CTB Distortions
IRC Plan	**0.5-MHz** relative to QAM channel center frequency.	**1.75-MHz** relative to QAM channel center frequency.
HRC Plan	**1.75-MHz** relative to QAM channel center frequency.	**1.75-MHz** relative to QAM channel center frequency.

15

To overcome the impact of CSO/CTB distortions using the
IRC plan at the QAM receiver, two pre-distortion filters
(one for CSO and one for CTB) with $H(z)^{-1}$ frequency
response are enabled in the QAM modulator, which is
5   located at the cable headend. Two notch filters with
$H(z)$ frequency response and with the same coefficients
are also enabled in the QAM receiver in the set-top box.
No adaptation is required here since the frequencies of
the nonlinear distortions are always known in hybrid
10   analog/digital HFC networks. For the HRC plan, only one
pre-distortion filter and one corresponding notch filter
are required, since CSO and CTB occur at the same
frequency.

It should now be appreciated that the present invention
15   provides methods and apparatus for filtering interference
and nonlinear distortions in communications systems.
Although the invention has been described in connection
with cable television systems, wherein the downstream
path may suffer from nonlinear distortions (CSO/CTB) and
20   the upstream path may suffer from ingress noise, the

invention is not limited to use in such systems or to

these types of interference and distortion. The novel

techniques for interference detection and reduction and

for filtering nonlinear distortion are applicable to any

5   communication system where such interference resides at

detectable or already known frequencies. By pre-

distorting the transmitted signal and filtering the pre-

distorted signal at the receiver, effective reduction or

elimination of interference and nonlinear distortion is

10   obtained. Accordingly, various adaptations and

modifications may be made to the invention without

departing from the scope thereof as set forth in the

claims.